Experimental and Numerical Investigation of the Influence of Drill Pipe Movement on Annular Mud Flow Field Distribution

Haitao Yan [1], Yaosheng Ding[2], Sheng Huang [2, 4], Xuefeng Yan [3,*], Baosong Ma [2, 4, 5], Jiguo Liu [1, 6]

[1]CCCC Second Highway Consultant Co., Ltd., Wuhan 430056, China
[2]School of Civil Engineering, Sun Yat-sen University, Zhuhai 519082, China
[3]Faculty of Engineering, China University of Geosciences, Wuhan 430074, China
[4]Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai 519080, China
[5]State Key Laboratory for Tunnel Engineering, Guangzhou 510275, China
[6]CCCC Tunnel and Underground Space Engineering Technology R&D Center, Wuhan 430056, China

*Corresponding author: Xuefeng YAN, cugyanxf@163.com

Abstract. Low migration efficiency of cuttings in large-diameter horizontal directional drill can easily cause various kinds of in-hole accidents. Drill pipe motion affects the distribution of the annular mud flow field, which indirectly affects the migration efficiency of cuttings, so it is very important to find out the effect of drill pipe motion on the annular mud flow field to solve the cuttings transportation problem. In this paper, the important parameters of drill pipe motion are modeled and studied, and the influence of drill pipe motion on the distribution of annular mud flow field is investigated by numerical simulation method. Drill pipe rotation speed and eccentricity are important parameters of drill pipe motion, and the numerical simulation results show that increasing the drill pipe rotation speed can increase the mud flow rate within a certain range, and the maximum axial flow rate of annular mud increases with the increase of the eccentricity of the drill pipe, but the range of the influence of the rotation of the drill pipe on the annular mud flow field gradually decreases. This paper reveals the influence of drill pipe motion on the distribution characteristics of the annulus mud flow field, which can provide a theoretical basis for research on cuttings transportation problems.

Keywords: trenchless; HDD, drill pipe motion; annular mud flow field; numerical simulation

1 Introduction

Horizontal directional drilling traversing technology originally originated from the oil drilling industry, which has been widely used in the construction of municipal pipelines

Y. Qiu et al. (eds.), *Proceedings of the 2024 7th International Conference on Civil Architecture, Hydropower and Engineering Management (CAHEM 2024)*, Advances in Engineering Research 256,
https://doi.org/10.2991/978-94-6463-650-5_47

and oil and gas pipelines by virtue of its advantages of high efficiency, safety and environmental protection, as well as low impact on the environment (Sun et al., 2022). After continuous engineering practice, horizontal directional drilling traversing technology has made great progress, and the diameter of laid pipe is also increasing. However, with the increase of pipe diameter, many problems also appear in the construction of directional drilling traversing (Soares et al., 2023). In the second line of west-east gas pipeline crossing project, with the increase of pipe diameter from 1016 mm to 1219 mm, the success rate of horizontal directional drilling once crossing decreased to less than 20 %, and the average number of accidents in each crossing hole was more than 3 times, and when the geological conditions were complicated, the number of accidents in the hole of a single crossing was even more than 10 times. The low efficiency of mud debris removal is an important reason for the frequent occurrence of accidents in large-diameter horizontal directional drill holes (Jin et al., 2022).

Among the main factors affecting the mud debris removal efficiency, the mud flow rate in the annulus and the mud rheological properties directly affect the mud debris removal efficiency, and the motion of the drill pipe affects the distribution characteristics of the mud flow field in the annulus, which indirectly affects the debris transportation efficiency (Adari, Miska and Kuru et al., 2000; Tomren, Iyoho and Azar, 1986). In order to improve the debris transport efficiency, for the above factors, scholars at home and abroad have carried out a lot of research (Wang and Zhang, 2010; Chen, Liu and Ding, 1992; Ozbayoglu and Saasen, 2010; Sanchez, Azar and Bassal et al., 1999; Ozbayoglu, Saasen and Sorgun et al., 2008), but these studies are mostly based on the characteristics of early oil drilling, such as small gap in the annulus of the borehole, turbulent flow of the mud and high average flow rate. The average flow velocity of annular mud in large diameter horizontal directional drilling is very low, and its annular mud flow field characteristics are very different from those of early oil drilling. At present, the research on chip removal efficiency in large-diameter horizontal directional drilling mostly focuses on the mud itself (Nathan, Brian and Demos, 2008; Cai and He, 2009; Hair, 1995; Allouche, 2002), and focuses on the influence of the return speed of the annulus, the rheological properties of the drilling fluid and other conditions on the effect of rock-carrying. While there are fewer studies on the effect of the mud flow field on the motion of the drill pipe, which do not link the movement of the drill pipe with the mud flow field, and less consideration is given to the effect of the rotational speed of the drill pipe, the eccentricity and other factors on the change of the mud flow field in the movement of the drill pipe.

This study examines the impact of the mud flow field on drill pipe motion under various rotating speed and eccentricity combinations in order to gain a better understanding of this relationship. Drawing from previous findings, this study examines the motion state of the drill pipe using numerical simulations and field measurements, with a particular focus on annular mud with a lower average flow rate. This work employed numerical simulation to examine the impact of drill pipe motion on the distribution features of the annulus's mud flow field, in addition to modeling experiments to investigate the current condition of drill pipe motion.

2 Study on the Motion State of Annular Drilling Rods

During the reaming stage of horizontal directional drilling, the drill pipe connection is shown in **Fig. 1**. The torque of the reamer, the self-weight of the drill pipe, the pulling force of the drilling rig, and the friction between the drill pipe and the hole wall all work together to cause the auxiliary drill pipe to rotate on a regular basis.

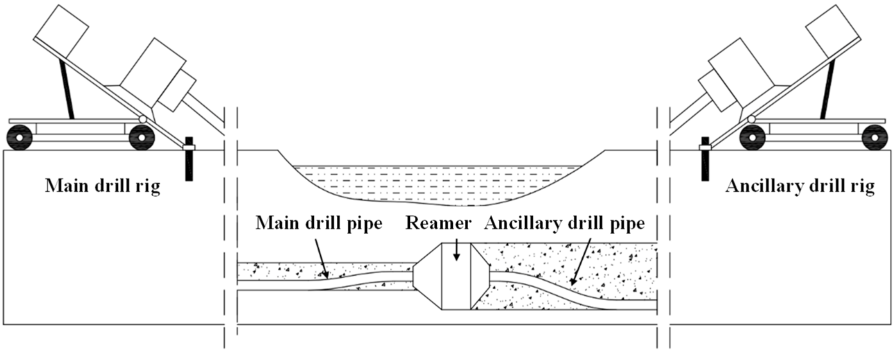

Fig. 1. Diagram of drill pipe connection during HDD expansion stage

2.1 Experimental Preparation

Due to type tests are extremely challenging to conduct equal-scale primate models with a similarity ratio of 1:2.7; instead, the similarity transformation approach is employed to simulate the actual working conditions inside the site and experimental conditions.

The model test parameters are shown in **Table 1**.

Table 1. Size parameter of model test

Project	Drill pipe diameter/ mm	Drill pipe outer diameter / mm	Wall thickness / mm	Drill pipe internal diameter / mm
Actual working conditions	1080	168.275	9.177 5	149.92
Experimental Model Study	400	63	3.5	56

The model test arrangement is shown in **Figs. 2** and **3**. A speed-regulated motor with a rated power of 2,000 kW and a rated speed of 2,000 rpm was used for the experiments and equipped with a reduction gearbox with a reduction ratio of 40:1 to provide the necessary rotary power for the drill pipe. At the same time, a tension transducer was connected to the end of the drill pipe to monitor the axial tension applied to the drill pipe. In order to simulate the constraints imposed on the drill pipe by horizontal directional drilling, a transparent acrylic pipe was installed at the end of the drill pipe. Furthermore, three laser displacement monitoring devices were positioned along the drill pipe's axial direction. The three monitoring sections were situated at distances of one, three, and five meters from the drill pipe's starting, respectively. Each section's two orthogonally positioned laser displacement sensors allowed for the simultaneous measurement of the drill pipe's vibration displacement in both XY directions.

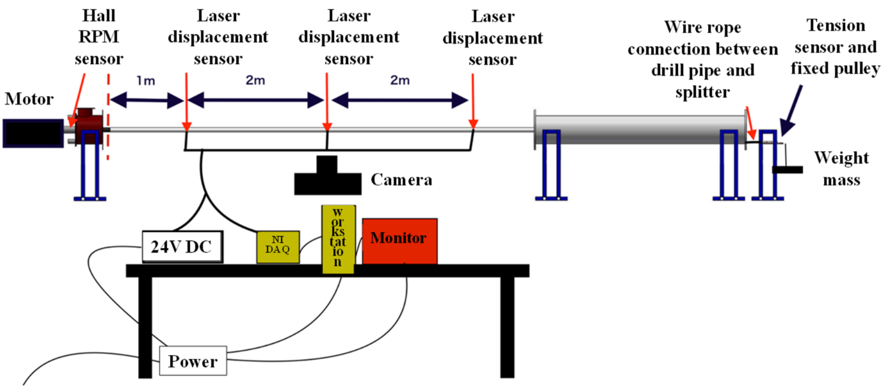

Fig. 2. Diagram of model test layout

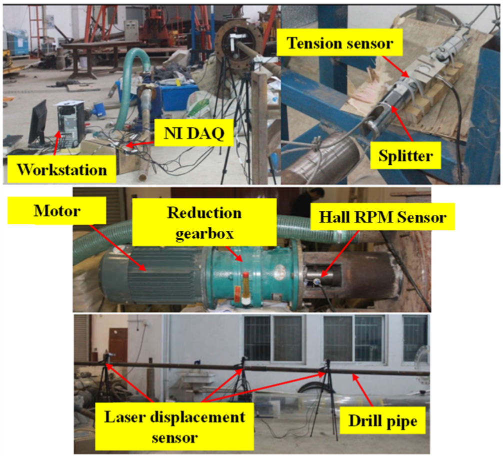

Fig. 3. Test site

2.2 Experimental procedure

(1) Construct a drilling pipe motion experimental model according to the aforementioned test plan.

(2) Install the laser displacement sensor, ensure that the sensor displays a displacement of 0 and record the relative position coordinates of the sensor.

(3) The tension sensor at the end of the drill pipe is connected to the weight mass through a pulley and a steel cable (no weight is suspended in the initial state).

(4) Use a frequency converter to adjust the rotational speed to 10 rpm, 20 rpm, 30 rpm, and 40 rpm. After the system vibration stabilizes, continuously take photographs at each speed for a duration of 10 seconds. Meanwhile, monitor the displacement and record the data during these 10 seconds.

(5) Sequentially increase the weight mass in the order of 10 kg, 20 kg, 30 kg, 40 kg, 50 kg, and 60 kg. After each weight increment, repeat step (4).

2.3 Experimental result

It can be seen from **Fig. 4** that with the increase of axial tension, the amplitude of the drill pipe in the horizontal direction in the measured cross section at the 3 m position at 20 rpm is significantly larger than the amplitude in the gravity direction. When the axial tension force changes, the vibration change in the gravity direction is relatively small. The combined amplitude range of the drill pipe in this cross-section reaches a minimum at tension forces of 100N and 400N. When the tension force is raised to 600N, irregular vibration phenomenon occurs in the drill pipe.

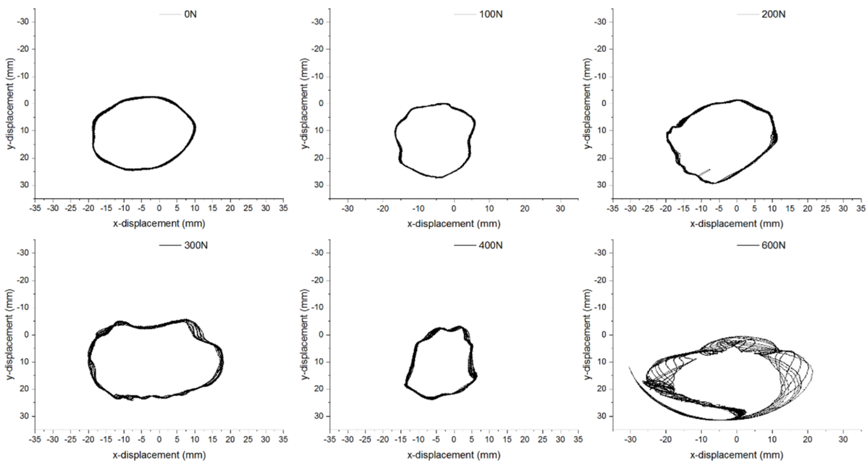

Fig. 4. Cross-section of drill pipe movement at 20 rpm with different axial pulling forces

Fig. 5 shows the measurement results of the three measurement sections under different rotational speed conditions at 200 N axial tension. It can be found that the third section is more affected by the hole wall constraint, and the vibration randomness is obviously larger than the first two sections. Meanwhile, with the increase of rotational speed, the motion of the drill pipe at the same measurement section becomes complicated gradually.

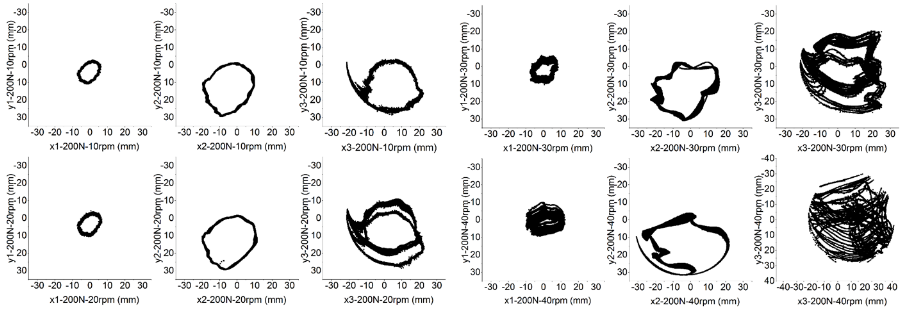

Fig. 5. Cross-section of drill pipe movement at different speeds under 200 N axial pulling force

In conclusion, eccentricity and rotating speed of the drill pipe have a significant impact on how the drill pipe moves. Drill pipe motion states can be categorized into three categories based on the drilling axis: eccentric rotation, eccentric revolution, and eccentric rotation under various combinations of rotational speed and eccentricity.

3 Numerical Simulation Study of Velocity Field of Annular Slurry

Since the annular space of large-diameter horizontal directional drilling is so large, it becomes difficult to rely solely on indoor experiments to study the distribution of the mud flow field. Traditional contact mud flow field monitoring systems, like rotating vane flowmeter, will obviously disturb the flow field during use, while non-contact systems, like ultrasonic Doppler flow field monitoring systems, are difficult to accurately measure the high-viscosity and non-transparent mud.

At present, general-purpose computational fluid dynamics (CFD) software, such as Fluent, COMSOL, etc., has been very mature, can effectively simulate the boundary conditions of the complex flow field and provide reasonable and reliable results, so this paper adopts the CFD software simulation to study the effect of the movement of the drilling rod on the flow field of the annular mud.

3.1 Numerical Simulation Conditions

The state of motion of the fluid can be described by the fluid continuity equation, the equation of motion, and the intrinsic equation, and the flow state of the fluid has uniqueness under the given initial values and boundary conditions. According to the differential equations of motion and boundary conditions of the annular flow field of horizontal directional drilling (yan, 2018), the annular mud flow in column coordinates is divided into two cases: annular flow and axial flow.

Based on the above, eccentricity and rotating speed of the drill pipe have a significant impact on how the drill pipe moves. Drill pipe motion states can be categorized into three categories based on the drilling axis: eccentric rotation, eccentric revolution, and eccentric rotation under various combinations of rotational speed and eccentricity. Consequently, in this numerical simulation study, various eccentricity conditions and rotational speeds were selected to combine into various drill pipe motion states. The rotational speeds of the drill pipes were selected to be 30 rpm, 60 rpm, 90 rpm, and 120 rpm in combination with various eccentricity distances, respectively.

Horizontal directional drilling final hole diameter is usually 1.2~1.5 times of the pipe diameter, the size of the numerical model is set with reference to the actual working conditions, in which the diameter of the pipe is 1016 mm, the diameter of the final hole is 1524 mm, and the diameter of the drilling rod is 168 mm. The simulated mud flow type is selected from the HBF, which has a better rheological curve and the actual mud, and the relevant parameters are shown in **Table 2**:

Table 2. Mud parameters of numerical model

Formula	Dynamic yield stress/ Pa	Flow behavior index	Consistency coefficient/ (Pa·s^n)
HBF	9.198	0.801	0.054

In order to investigate the effects of drill pipe rotational speed and eccentricity on the annular and axial flow fields of annular mud, the simulation experiments were conducted using orthogonal experimental methods, and the experimental setups are shown in **Tables 3** and **4**:

Table 3. Numerical simulation test group of annular flow field

Flow pattern	eccentricity/ mm	Drill rod speed/ rpm	Simulation test number
HBF	0	30	A
	0	60	B
	0	90	C
	0	120	D
	200	30	E
	400	30	F
	670	30	G
	center of circle 300	30	H
	center of circle 300	60	I
	center of circle 300	90	J
	center of circle 300	120	K

Note: The notation "center of circle 300" indicates that the center of rotation for the drill rod is located 300 mm below the center of the borehole.

Table 4. Numerical simulation test group of axial flow field

Flow pattern	eccentricity/ mm	Drill rod speed/ rpm	Axial Mean Flow Rate/ (m/s)	Simulation test number
HBF	0	30	0.01	L
	200	30	0.01	M
	400	30	0.01	N

600	30	0.01	O
400	60	0.01	P
400	90	0.01	Q
400	120	0.01	R

3.2 Numerical Simulation Results and Analysis

Effect of Drill Pipe Rotational Speed on the Mud Annular Flow Field. Simulation tests A~D investigate the effect of concentric drill pipe rotational speed on the annular flow field, and the simulation results are shown in **Fig. 6**:

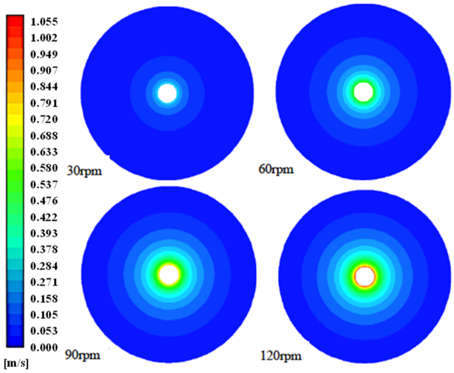

Fig. 6. Circumferential flow field distribution of concentric annulus with different drill pipe speeds

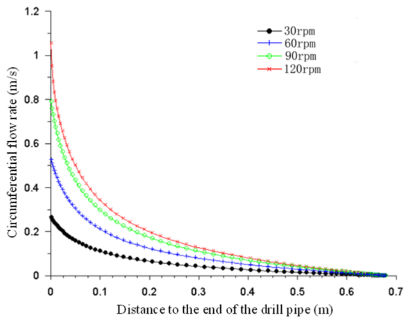

Fig. 7. Circumferential velocity of mud distribution along radial direction with different drill pipe speeds

From **Fig. 7**, it can be seen that with the increase of the rotational speed of the drill pipe, the annular flow rate of the mud within the same radius increases accordingly. The shear rate of annular mud changes dramatically at the 0.2 m position, and the annular mud flow field decays more quickly within the 0.2 m radius. Conversely, the more quickly the drill pipe rotates, the more evidently the annular mud flow rate decays; outside of the 0.2 m radius, the annular mud flow rate changes less noticeably and the shear rate tends to be similar.

Effect of Drill Pipe Eccentricity on the Mud Annular Flow Field. Simulation tests A, E~G study the effect of drill pipe eccentricity on the flow field in the annulus, and the simulation results are shown in **Fig. 8**.

The distribution of annular mud flow rate along the vertical direction (bottom-up) of the borehole for different eccentricity distances is shown in **Fig. 9**.

An increase in eccentricity will cause a gradual decrease in the scope of the mud flow field affected by the drill pipe's rotation, near the mud "reflux" phenomenon near the borehole wall, but it will also become more and more evident, as illustrated in **Fig. 10**. It is evident that the emergence of the drill pipe eccentricity causes the top and bottom of the drill pipe mud flow field distribution along the vertical direction of the borehole to show an asymmetric trend.

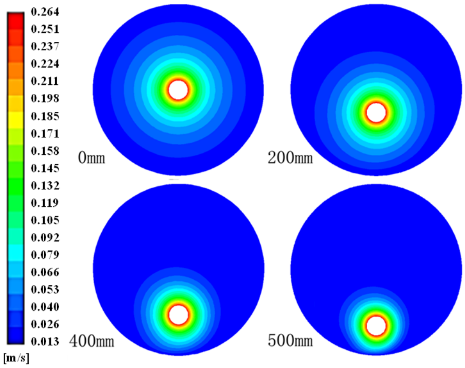

Fig. 8. The circumferential flow field distribution of mud with different eccentricity

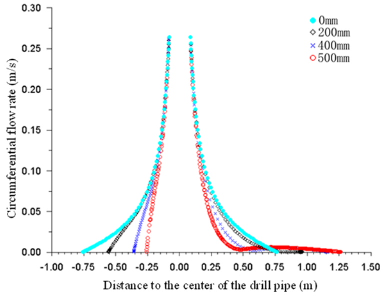

Fig. 9. The circumferential velocity of mud distribution along radial direction with different eccentricity

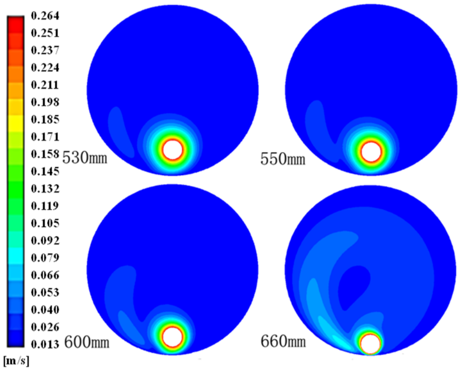

Fig. 10. The circumferential flow field distribution of mud with eccentricity of 530mm and 660 mm

Effect of Drill Pipe Rotation on the Mud Annular Flow Field. Setting the same rotational speed and rotational radius of 100mm, the simulation test H~K was conducted to study the influence of the rotational speed of the drill pipe on the flow field in the annulus.

As illustrated in **Fig. 11**, with a drill pipe rotational speed of 30 rpm, the mud flow field caused by the drill pipe's rotation is roughly shaped like a circle with its center of rotation, and the region at the "back" of the drill pipe has the highest mud flow velocity.

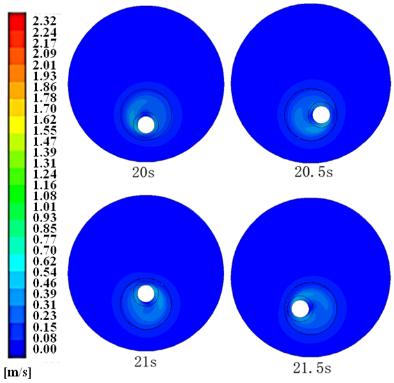

Fig. 11. Circumferential flow field distribution at 30 rpm

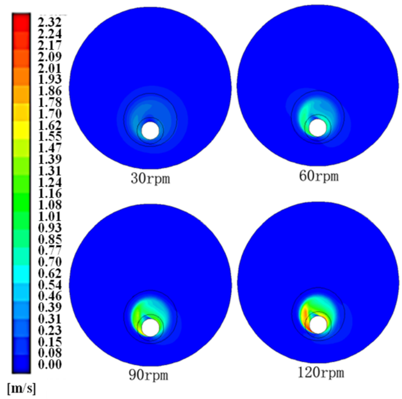

Fig. 12. Circumferential flow field distribution under different revolution angular velocity

The range of the annular flow field of the annular mud affected by the drill pipe's rotation is no longer circular in **Fig. 12**, as the drill pipe's rotational speed increases and its influence on the mud velocity in the tangential direction gradually increases.

Fig. 13 illustrates the positively proportional relationship between the maximum annular flow velocity of mud and the linear velocity of drill pipe rotation. However, as the distance from the mud to the center of rotation increases, the mud annular velocity rapidly decreases, and when the distance exceeds 0.2 meters, the rotation velocity has very little effect on the annular flow field. When comparing the 3.2.2 simulation results, it is evident that the maximum annular flow velocity of mud produced by the drill pipe's rotation is greater than the drill pipe's rotation at an angular velocity of 30 rpm.

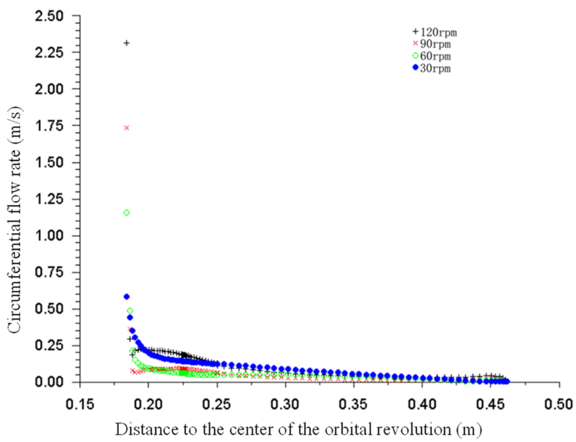

Fig. 13. The circumferential velocity distribution at the narrowest part of the annulus when the drill pipe is at the lowest point

Effect of Drill Pipe Eccentricity on Axial Flow Rate. A three-dimensional annular mud model was created, as illustrated in **Fig. 14**, with an average axial flow rate of 0.01 m/s and a drill pipe rotation speed of 30 rpm, in order to examine the effects of the eccentricity distance and the drill pipe's rotational speed on the annular mud's axial flow field.

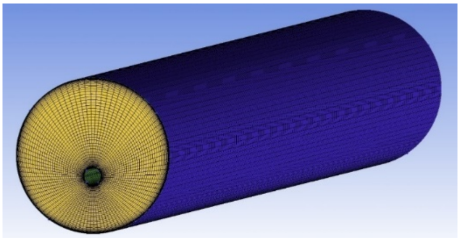

Fig. 14. Three-dimensional model of annular mud

Simulation test L~O investigates the effect of eccentricity distance on axial flow rate. **Fig.15** illustrates that the maximum axial flow rate in the annulus increases as the eccentricity distance increases in the range of 0~400mm. However, when the eccentricity distance is in the range of 400~600mm, the phenomenon of mud "reflux" near the hole wall causes the maximum axial flow rate to gradually decrease as the eccentricity distance increases. This means that the distribution of the axial flow field in the annulus is no longer symmetric about the drill pipe's center. Due to the occurrence of mud "backflow" near the hole wall, when the eccentricity is between 400 and 600 mm, the maximum axial flow velocity in the annulus will decrease as the eccentricity increases.

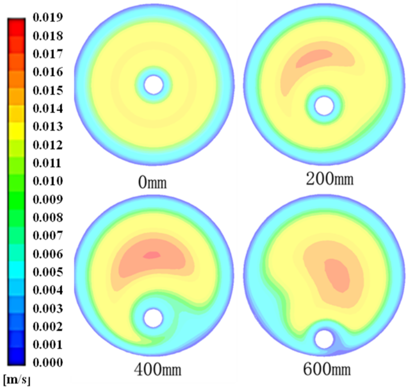

Fig. 15. The influence of different eccentricity on axial velocity

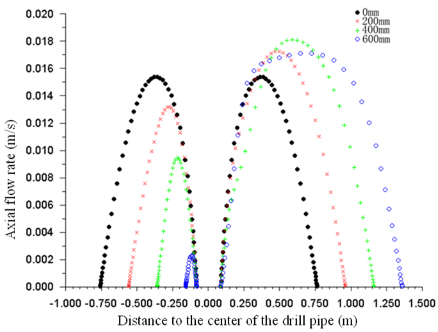

Fig. 16. The axial velocity of annular mud distribution along the radial direction under different eccentricity conditions

The radial distribution curves of the mud axial flow rate under various eccentricity settings, as shown in **Fig. 16**, exhibit similar patterns, with low mud flow rate near the drill pipe's surface and the hole wall and high mud flow rate at the drill pipe's center and the hole wall. Simultaneously, the maximum axial flow rate of mud in the annulus is directly proportional to the distance between the drill pipe's surface and the hole wall; that is, the size of the maximum axial flow rate of mud in the annulus is determined by the distance between the two.

Effect of Drill Pipe Speed on Axial Flow Rate. The model test N, P~R investigates the effect of the drill pipe rotational speed on the axial flow rate. it can be seen from **Fig. 17** that the axial velocity on the surface of the drill pipe gradually exceeds the average axial flow rate of the mud in the annulus as the rotational speed increases. When the rotational speed of the drill pipe is in the range of 30~90rpm, the region with the highest velocity in the velocity distribution cloud diagram gradually moves from the annulus hollow position to the small concentric ring near the drill pipe as the rotational speed increases; when the rotational speed of the drill pipe reaches 120rpm, the axial velocity of the mud near the drill pipe follows the influence law of the change of the rotational speed of the drill pipe, and the axial velocity of the mud in the rest of the positions follows the influence law of the change of the eccentricity of the drill pipe.

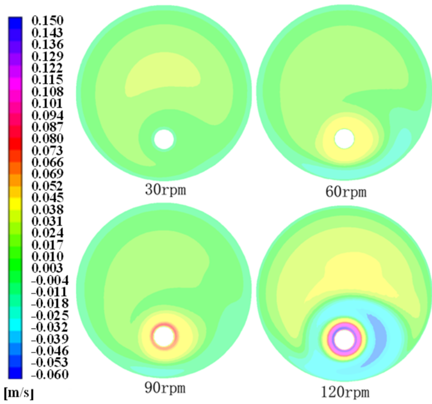

Fig. 17. The influence of different rotational speeds on the axial flow field

4 Discussions

4.1 Reasons Why the Movement of Drill Pipe Affects the Mud Flow Field

(1) Centrifugal force: The centrifugal force generated by the rotation of the drill pipe makes the mud move towards the wall of the drill hole, forming a circumferential flow.

(2) Eccentricity effect: When the drill pipe is eccentric, the centrifugal force is not uniform, resulting in asymmetric mud flow and local reflux phenomenon.

(3) Shear force: The friction between the drill pipe and the mud, and between the mud and the borehole wall generates shear force, which affects the mud flow speed and direction.

(4) Reynolds number: The movement parameters of the drill pipe and the rheological characteristics of the mud together determine the Reynolds number, which affects the flow pattern (laminar or turbulent) and the flow pattern.

4.2 Effect of Mud Flow Field on HDD Operation

(1) Debris Transportation Efficiency: The flow rate and flow pattern of annular mud directly affect the debris transportation efficiency. There are two ways to improve the efficiency, namely, to increase the flow rate and to improve the flow pattern. Increase the flow rate: Rotation and revolution of the drill pipe can increase the flow rate of the mud in the annulus, which can help to carry the rock chips and improve the efficiency of chip removal. Improve flow pattern: The localized reflux caused by the eccentricity of the drill pipe can help to remove the rock chips near the drilling wall and prevent the accumulation of rock chips and jamming of the drill.

(2) Drilling fluid performance: Drill pipe movement affects the rheological properties of the drilling fluid, which in turn affects its rock-carrying capacity and stability.

(3) Tool wear: Mud flow caused by the movement of the drill pipe will increase the wear of the drilling tools, which requires regular inspection and maintenance.

(4) Hole wall stability: Mud flow will affect the stability of the hole wall, and it is necessary to reasonably control the mud properties and flow rate to prevent hole collapse.

5 Conclusions and Recommendations

Through modeling tests, it is determined in this work that the eccentricity and drill pipe's rotational speed play significant roles in determining the drill pipe's motion state. A numerical model is established to analyze the effects of eccentricity and drill pipe rotation speed on the annular mud flow field's distribution characteristics. This model is based on the annular mud's boundary conditions, velocity distribution equations, and equations of motion in cylindrical coordinates.

Through modeling tests, it is determined in this work that the eccentricity and drill pipe's rotational speed play significant roles in determining the drill pipe's motion state. An analysis of the effects of drill pipe rotation speed and eccentricity on the distribution characteristics of the annular mud flow field is done numerically using the equations of motion, velocity distribution equations, and boundary conditions of the annular mud in cylindrical coordinates. An increase in drill pipe rotation speed can increase both annular and axial velocities within a certain range of the annular mud field, and it can also increase the maximal annular velocity, provided that the maximal annular velocity generated by the drill pipe rotation is greater than the maximal mud velocity generated by the drill pipe rotational speed. In addition, the maximum annular velocity produced by the drill pipe's rotation is greater than the maximum annular velocity produced by the drill pipe's rotation. The maximum axial velocity of the annular mud increases as drill pipe eccentricity increases, yet the drill pipe's range of influence on the annular flow field decreases.

More research is required because, while this paper shows how drill pipe motion affects the annular mud flow field's distribution features in the annulus, it does not examine the impact of rock chip movement or flow field change. Future modeling experiments will be conducted to validate the paper's conclusions.

References

1. Sun P., Liu W., Yang H., Wei B., Xia Y. 2022. Progress in research and applications of trenchless horizontal directional drilling equipment and technology in China[J]. Chinese Journal of Engineering, 2022, 44(1): 122-130.
2. Soares A., Danziger F., Domingos G. 2023. An experimental study of Horizontal Directional Drilling (HDD) in sand in a large flexible calibration chamber. Tunnelling and Underground Space Technology, 141, 105295.
3. Jin, L.; Wei, J. 2022 Research on Horizontal Directional Drilling (HDD) Trajectory Design and Optimization Using Improved Radial Movement Optimization. Appl. Sci. 2022, 12, 12207.
4. Adari R B, Miska S, Kuru E, et al. 2000. Selecting drilling fluid properties and flow rates for effective hole cleaning in high-angle and horizontal wells[C] //SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.
5. Tomren P H, Iyoho A W, Azar J J. 1986. Experimental study of cuttings transport in directional wells[J]. Spe Drilling Engineering, 1(01): 43-56.
6. Wang Z., Zhang Z. 2003. Study on the rock chip transport law of two-layer stabilization model for large inclined wells[J]. Oil drilling process, 25(4): 8-11.
7. Chen J., Liu X., Ding G. 1992. Experimental study of rock-carrying in the annulus of horizontal well sections[J]. Journal of Petroleum University: Natural Science Edition, 16(4): 23-26.
8. Ozbayoglu M E, Sorgun M, Saasen A, et al. 2010. Hole cleaning performance of light-weight drilling fluids during horizontal underbalanced drilling[J]. Journal of Canadian Petroleum Technology, 49(4):21-26.
9. Sanchez R A, Azar J J, Bassal A A, et al. 1999. Effect of drillpipe rotation on hole cleaning during directional-well drilling[J]. SPE Journal, 4(02): 101-108.
10. Ozbayoglu M E, Saasen A, Sorgun M, et al. 2008. Effect of pipe rotation on hole cleaning for water-based drilling fluids in horizontal and deviated wells[C]//IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. Society of Petroleum Engineers.
11. Nathan Wicksa, Brian L. Wardleb, Demos Pafitisc. 2008. Horizontal cylinder-in-cylinder buckling under compression and torsion: Review and application to composite drill pipe[J]. International Journal of Mechanical Sciences, (50):538–549.
12. Cai L X, He L M. 2009. Mechanical model for determining the crossover point of slurry flow in pull-back of horizontal directional drilling installations[J]. ICPTT 2009 © 2009 ASCE.
13. Hair J D. 1995. Directional drilling demands practical fluids knowledge[J]. Pipe Line and Gas Industry, ,78(8): 32-37.
14. Allouche E.A. 2002. Implementing quality control in HDD projects – a north American prospective[J]. Journal of Tunnelling and Underground Space Technology, 16(1): S3-S12.
15. Yan X. 2018. Research on rock chip transportation law of large diameter non-excavation horizontal directional drilling[D]. China University of Geosciences.